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**NUMERICAL SIMULATION OF ONE- AND TWO-PHASE
FLOWS IN PROPULSION SYSTEMS**

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NUMERICAL SIMULATION OF ONE- AND TWO-PHASE FLOWS IN PROPULSION SYSTEMS

In this report, we present some results of problems investigated during joint research between the Hampton University Fluid Mechanics and Acoustics Laboratory (FM&AL), NASA Glenn Research Center (GRC) and the Hyper-X Program of the NASA Langley Research Center (LaRC). This work is supported by joint research between the NASA GRC/HU FM&AL and the Institute of Mechanics at Moscow State University (IM/MSU) in Russia under a Civilian Research and Development Foundation (CRDF) grant, #RE1-2068. The main areas of current scientific interest of the FM&AL include an investigation of the proposed and patented advanced methods for aircraft engine thrust and noise benefits. These methods are based on nontraditional 3D corrugated and composite nozzle, inlet, propeller and screw designs such as the Bluebell and Telescope nozzles, Möbius-shaped screws, etc. These are the main subject of our other projects, of which one is the NASA MURED's FAR Award, #NAG-3-2249. Working jointly with this project team, our team also analyzes additional methods for exhaust jet noise reduction. These methods are without essential thrust loss and even with thrust augmentation. Such additional approaches are:

A) To add some solid, fluid or gas mass at discrete locations to the main supersonic gas stream to minimize the negative influence of strong shock waves formed in propulsion systems. This mass addition may be accompanied by heat addition to the main stream as a result of the fuel combustion or by cooling of this stream as a result of the liquid mass evaporation and boiling.

B) Use of porous or permeable nozzles and additional shells at the nozzle exit for preliminary cooling of the hot jet exhaust and pressure compensation for off-design conditions (so-called continuous ejector with small mass flow rate).

C) To propose and analyze new effective methods for fuel injection into the flow stream in air-breathing engines.

The research is focused on a wide regime of problems in the propulsion field as well as in experimental testing and theoretical and numerical simulation analyses for advanced aircraft and rocket engines. The FM&AL Team uses analytical methods, numerical simulations and experimental tests at the Hampton University campus, NASA and IM/MSU. The main results obtained by FM&AL team were published in the papers and patents [1-10].

The main outcomes during this reporting period are:

1) Publications:

1.1 The AIAA Paper #01-1893, entitled: "Corrugated and Composite Nozzle-Inlets for Thrust and Noise Benefits" and written by M. Gilinsky, I.M. Blankson, V.G. Gromov, and V.I. Sakharov has been presented at the AIAA/NAL-NASDA-ISAS 10th International Space Planes and Hypersonic Systems and Technologies Conference on 24-27 April 2001, Kyoto, Japan.

1.2 The AIAA Paper #01-3204, entitled: "Shock Waves Mitigation at Blunt Bodies Using Needles and Shells against a Supersonic Flow" and written by M. Gilinsky, I.M. Blankson, V.A. Sakharov, and A.I. Shvets has been presented at the 37th AIAA/ASME/SAE/ ASEE Joint Propulsion Conference on 08-11 July, in Salt Lake City, UT.

1.3 Gilinsky M., Blankson I. M., Ivanov O.N., Shvets A.I., 2001, Experimental research of a flow of the blunted bodies with lobbed needles, IV International Conference "Actual problems of the

mechanics of continuous and loose environments". National Academy of Applied Sciences, January 21-23, 2001, Moscow, Russia.

1.4 Gilinsky, M., Patel, K., Alexander, C., Thompson T., Blankson, I.M., Shvets, A.I., Gromov, V.G., Sakharov V.I., 2001, Numerical Simulation of One- and Two-Phase Flows in Propulsion Systems, HBCUs/OMUs Research Conference Agenda and Abstracts, OAI/NASA GRC, April 17-18, 2001, p.23.

1.5 Gilinsky, M., Morgan, M.H., Povitsky A., Blankson I.M., 2001, Advanced Methods for Aircraft Engine Thrust and Noise Benefits: Nozzle-Inlet Flow Analysis, HBCUs/OMUs Research Conference Agenda and Abstracts, OAI/NASA GRC, April 17-18, 2001, p.22.

1.6 Gilinsky, M., Washington C., Blankson, I.M., and Shvets A.I., 2002, Spike-Nosed Bodies and Forward Injected Jets in Supersonic Flow, the abstract submitted for presentation at the 38th AIAA/ASME/SAE/ ASEE Joint Propulsion Conference on July 7-10, 2002, Indianapolis, IN.

1.7 Morgan, M.H., Gilinsky, E., and Maron, V.I., 2002, Re-Circulation Method and Heat Transfer Enhancement in Propulsion Systems, the abstract submitted for presentation at the 38th AIAA/ASME/SAE/ ASEE Joint Propulsion Conference on July 7-10, 2002, Indianapolis, IN.

1.8 Hardin, J.C., and Gilinsky, M., 2002, Infrasonic Atmospheric Monitoring, the abstract submitted for presentation at the 9th International Congress on Sound and Vibration, on July 8-11, 2002, Orlando, FL.

1.9 Hardin, J.C., and Gilinsky, M., 2002, Environmental Monitoring via Infrasound, the abstract submitted for presentation at the 8th AIAA/CEAS Aeroacoustics Conference & Exhibit on June 17-19, Breckenridge, CO.

2) New proposals:

2.1 The unsolicited proposal entitled: "Injection, Mixing and Combustion Enhancement via Pulse Detonation Engine Application" was submitted to the NASA GRC, and currently, it is under a review.

2.2 Three Notice of Intent with the abstracts were submitted for the 2002 FAR Awards competition (NRA 02-OEOP-05) by the FM&AL Team members as PIs: 1) Dr. Vadivel Jagasivamani "Measurement Technique Improvement for Aerodynamic Tests in Low Speed Wind Tunnel"; 2) Dr. Arun Verma, "Pulse Detonation Engine Concepts Analysis: Injection, Mixing and Combustion Enhancement"; 3) Dr. Abolghassem Miamiee, "Nuclear Test Location Via Infrasound-A New Approach".

2.3 The White Paper entitled: "Aeropropulsion Hampton University Research Engineering and Technology Institute (APHURETI)" has been submitted to the NASA CAN 01-OAT-01 competition and accepted by NASA.

2.4 The proposal entitled: "Investigation of Periodic Detonation Processes and Mixing of Gases in Supersonic Flows" has been submitted to the CRDF Cooperative Grants Program for joint research between US Team representing by the NASA LaRC-HU FM&AL and Russian Team representing by the IM/MSU but was not awarded.

2.5 The proposal entitled "Theoretical and Experimental Research of Optimum Aerodynamic Forms-Waveriders" has been submitted to the CRDF Cooperative Grants Program. This proposal is for joint research between US Team represented by the NASA GRC-HU FM&AL and Russian Team represented by the Central Research and Development Institute of Machine Building (TsNIIMACH) but was not awarded.

2.6 The solicited White Paper entitled: "Advanced Nozzle and Inlet Designs for Air-Breathing Propulsion System" was submitted for the NASA NRA-01-GRC-02 competition but was not awarded.

3) Theory and numerical simulations:

Analytical theory, numerical simulations, comparison of theoretical with experimental results, and modification of theoretical approaches, models, grids etc. have been conducted for three main problems. **a)** Optimization of combustion efficiency has been studied for the half-duct combustor system. **b)** Drag reduction effects for blunt bodies with solid needles. And **c)** Solid particle and liquid jet injection from the butt-end against a supersonic airflow. The NASA CFL3D, FM&AL and IM/MSU GODUNOV codes were used and modified for solution of these problems. The codes are based on full Euler and Navier-Stokes solvers with and without non-equilibrium oxygen-nitrogen and air-hydrogen chemical reactions in laminar and turbulent gas flow regimes.

4) Experimental tests:

In the IM/MSU supersonic wind tunnel, A-7, experimental tests were conducted with different number, location and geometric parameters of solid needles mounted at the front of the butt-end in supersonic flow. Optimal parameters were determined that provide minimal butt-end drag in the stationary flow regime. Also, several tests were conducted for liquid jet injection at the front of the butt-end with the same goal. Experimental and numerical simulation results are in good agreement. Also, experimental tests of several Möbius-shaped screws were conducted at the Hampton University campus using the FM&AL experimental test facilities, in particular, the Low Speed Wind Tunnel (LSWT).

5) Student Research and Training Activity:

Hampton University students were involved as research assistants in the current project fulfillment. These students are: graduate students, Kaushal Patel and Debrup Banerjee (Computer Science Dept.) undergraduate students, Tyesha Thompson (Computer Science Dept.), Casey Alexander, Norman Njoroge (Aviation Dept.), and Calvin Coston (Electrical Engineering Dept.).

7) Illustrations and Comments:

In conclusion, some achievements of our Team during the reporting performance period will be illustrated in Figures 1-8.

7.1 Bluebell and Telescope Nozzles; Figures 1 and 2

Several well-known experimental results show essential acoustic benefits in the application of some untraditional nozzle designs. For example, nozzles with rectangular or elliptic cross section in the supersonic part produce less jet noise than round nozzle designed for a fixed Mach number at the nozzle exit (i.e. with uniform flow at the exit and pressure coinciding with the flight static pressure outside the exhausting jet). Thus, the theoretical perfectly shock free jets are "noisier" than at least partially underexpanded (or overexpanded) jets with possible internal shocks. Moreover, several experimental researches have shown that inserting disturbing elements into supersonic jet flow: slots, finger, tabs etc., can reduce jet noise (and screech tones) in spite of the presence of numerous strong and weak shock waves. This contradicts the traditional view of the considered phenomenon. A reasonable explanation for these facts would be the appearance of more effective mixing and destruction of the regular cell-shock structure in the weakly underexpanded jet. Inside such a jet, weak barrel-shaped shock waves are always present and these shock waves are the main sources of the

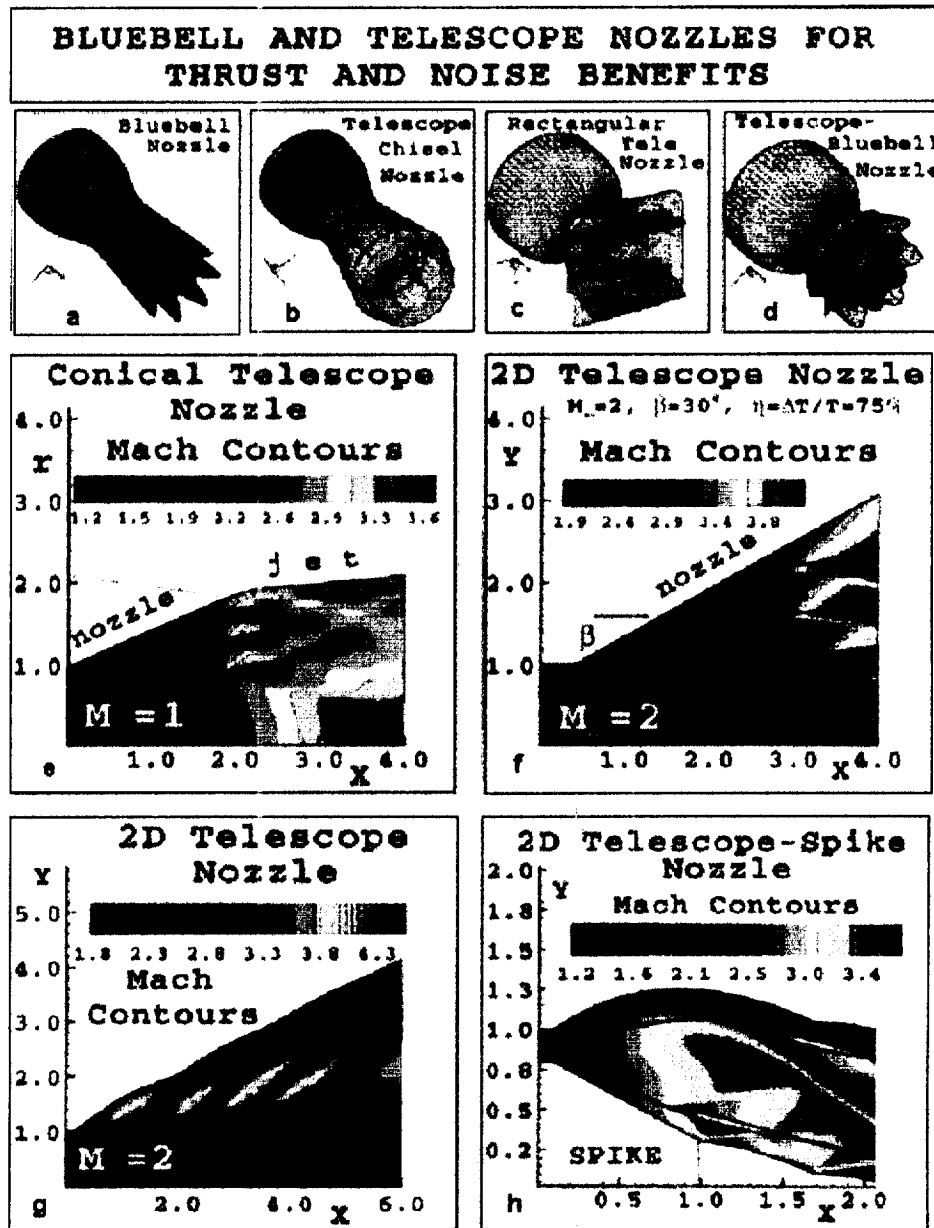


Fig.1 Bluebell and Telescope-shaped nozzles and numerical simulation results.

- a) The 8-petal Bluebell Nozzle. b)-d)-Different Telescope nozzles with one internal portion mounted inside the main external nozzles. e)-h)-Numerical simulation results for Telescope nozzles with multiple internal portions, Mach contours based on the TECPLOT-9 application.

oscillatory processes in the jet. In the regular almost parallel co-annular mixing layers, unstable longitudinal waves are excited, and noise is produced in a fixed direction from the jet axis $\sim 145^\circ$. Of course, the presence of shock waves in the jet exhaust, especially for a supersonic nozzle, can lead to some dangerous side effects and performance penalties.

Developing previous ideas for jet noise reduction, two novel concepts were proposed in the papers of J.M. Seiner and M. Gilinsky. The first concept is denoted as the Bluebell nozzle, based on the flower-like shape of its external jet plume. Bluebell nozzles utilize both chevrons and corrugation in their nozzle geometry. An example of such a design is shown in Figure 1a. The second concept is denoted as the Telescope nozzle for it consists of several internal nozzle surfaces that are arranged in a telescope fashion. Each concept is capable of achieving a thrust performance greater than the standard baseline conic or 2D plane convergent and convergent-divergent (CD) nozzles. The improved performance of Bluebell nozzles occurs due to the increase in nozzle internal surface area while maintaining the same nozzle projected area as the baseline nozzle.

Small scale and large-scale acoustic tests of different modifications of Bluebell nozzles were conducted at the NASA Langley Research Center and the Central AeroHydrodynamics Institute (TsAGI) in Moscow, Russia. These tests have shown essential acoustic benefits of Bluebell design applications in supersonic regimes as well as in subsonic regimes. For example, the experimental tests of several Bluebell nozzle designs have shown noise reduction relative to a CD round nozzle with design exhaust Mach number $M_e=1.5$. The best design provides an acoustic benefit near 4dB with about 1% thrust augmentation.

The second, Telescope-shaped nozzle concept was proposed by the same researchers with the goal of design optimization for the maximum nozzle thrust for the intended application of this concept to propulsion systems, especially, for a supersonic engine inlet and in stationary detonation engines.

A divergent flow can act on a plate or airfoil inserted into a flow so that a resulting force is directed against the flow. This effect is used for thrust by supersonic nozzles. Conversely, a uniform flow produces only drag for bodies and airfoils. Inserting a conical or wedge-shaped nozzle inside the divergent part of an external nozzle so that the integral of the pressure on the low side of the inserted surface is greater than on the upper side produces increased thrust. There is an optimal angle of the plate that provides the maximum thrust at each point of a divergent flow. The most efficient internal design is produced from a pattern that looks like a telescope with extending tubes. The optimal number of internal designs is defined through dependence on the Mach number at the nozzle exit, M_e . Telescoping designs must be located so that the compressible waves formed by interaction of a flow with this design would be passed on to the upper side of the next lower telescoping part. The best result will be produced by such a set if the external design inclination increases downstream. Computations show that a significant thrust benefit from the Telescope nozzle occurs with an external telescoping design, using either wedge, conical or optimal contour shapes, and also in the case of a plug application. Several examples of Telescope nozzles are shown in Figure 1b-d. Different holders can be used to keep internal designs inside the main external designs. Some combined approaches allow increasing the telescoping effects leading to nozzle thrust augmentation by Bluebell nozzle design application as well as to simultaneous noise reduction.

A numerical simulation analysis of different Telescope-shaped nozzle designs was conducted using inviscid approximation with the 1st order marching Krayko-Godunov scheme [3,4] as well as the

IM/MSU numerical code based on full Navier-Stokes equations for non-equilibrium gas mixture turbulent flows. The thrust calculations for the Telescope nozzle with one to four internal designs have shown that the benefits can be increased with several internal design applications. Their location and angles to the thrust direction should be chosen so that each shock wave formed at the lower side of the upper design would not intrude upon the upper side of the lower design. Similarly, each rarefaction wave formed at the upper side of the lower design should not intrude upon the lower side of the upper design. Figures 1e-g illustrate this approach for three, four internal components for axisymmetric and 2D Telescope nozzles, and Figure 1h illustrates it for Telescope-Spike nozzle with two internal airfoil-shaped designs. Here Mach contours and four streamlines (black solid lines) are presented.



Fig.2 NASA Langley Research Center Director, Dr. Jeremiah F. Creedon (on the right), congratulates the US patent authors, Dr. John M. Seiner (center), former NASA LaRC Senior Scientist and Dr. Mikhail Gilinsky (on the left), Hampton University Research Professor and Principal Investigator in the current project. A U.S. patent #6,082,635 entitled: “Undulated Nozzle for Enhanced Exit Area Mixing” has been granted to these authors on July 20, 2000, and an Award Ceremony took place on August 21, 2001 at the NASA LaRC HJE Reid Conference Center.

These streamlines correspond to the internal airfoil stagnation points and also represent the zone boundaries. An analysis of numerical results has the essential benefits of internal design applications. For example, in the case shown in Figure 1f, the inlet Mach number is $M_\infty=2$, the angle $\beta=30^\circ$, and the thrust augmentation for divergent nozzle portion is $\eta=\Delta T/T\sim 75\%$. Note that the working efficiency of a Telescope nozzle grows as the inlet Mach number increase; for $M_\infty=5$, the value of η can mount to $\sim 100\%$. This value can be even larger depending on the angle β . For the optimal angle of the main wedged or conical nozzle ($\sim 15\text{-}20^\circ$), thrust benefits are less and its can reach $\sim 30\%$.

Several Telescope-shaped nozzle designs were tested using the Russian IM/MSU code based on the full Navier-Stokes equations for two gas-phase models. For pure air nozzle-jet flow, the model of chemically frozen nitrogen-oxygen stoichiometric mixture with equilibrium excited of internal degrees of freedom is used. For the premixed hydrogen-air mixture exhausted from a divergent supersonic nozzle to the supersonic co-flow, the simplest non-equilibrium model of 7 components H_2 , O_2 , N_2 , H_2O , O , H , and OH with 8 chemical reactions is employed. Geometric wave shock-rarefaction pictures obtained in these simulations, are similar to obtained in the previous simulations, in particular, shown in Figures 1e and 1f. The composition of the inlet mixture is assumed to be in chemical equilibrium. These jet flows exhaust to the supersonic air co-flow with Mach number, $M_\infty=2$.

Finally, an analysis of computational results has shown that, for air-hydrogen or nitrogen-air non-equilibrium reacting gas flow, the thrust increase in the telescope nozzle is identical to that for a perfect gas flow. For high enough Reynolds numbers in the range of, $Re=10^6\text{-}10^7$, the maximal thrust losses by viscous effects (by friction forces at the internal designs and at the main internal conical nozzle wall) are only approximately 6-7%. Note that the maximal thrust augmentation, based on inviscid calculation by a simple 1st order marching numerical scheme, can reach up to 30% and even more. The main results of this research were presented at two conferences and published in the proceedings [6,8].

7.2 Shock Waves Mitigation at Blunt Bodies using Needles and Liquid Jets against a Supersonic Flow. Figures 3 -6

This paragraph contains some experimental and numerical simulation test results on cylindrical blunt body drag reduction using thin single or multiple spikes as well as fluid or particle injection to control shock waves and provide cooling for a body in high-speed flows or shell mounted in front of a body against a supersonic flow. Experimental tests were conducted using the Aeromechanics and Gas Dynamics Laboratory facilities at the Institute of Mechanics of Moscow State University (IM/MSU). Numerical simulations utilizing NASA and IM/MSU codes were conducted at the Hampton University Fluid Mechanics and Acoustics Laboratory. The main purpose of this research is to examine the efficiency of application of multiple spikes for drag reduction and flow stability at the front of a blunt body in different flight conditions, i.e. Mach number, angle of attack, etc.

7.2.1 Experimental Test Results. Spike-Nosed Blunt Bodies. Experimental tests were conducted using an axisymmetric cylindrical model with a flat forward part, i.e. butt-end, of diameter, $D=80\text{mm}$. Two types of models were tested: a) with 1 needle ($n=1$) and b) with 5 needles ($n=5$). Several such designs are shown in Figure 3. In both cases, one central needle was mounted at the center of the circular front flat part of radius, $R=40\text{mm}$. For the second series of models, another 4 needles were placed symmetrically around the central needle. They were placed at the angular interval of 90° and at the radial distance, $r=0.5 R$. Non-dimensional needle lengths, L/D , were chosen based on constructive

opportunities of application, and on known referenced data in this field. These data show that maximum drag reduction using needles at supersonic speeds can be achieved in the range of needle lengths, $L/D=1.5-2.0$, so that three needle lengths were manufactured and tested: $L/D=1.5$, 1.0 , and 0.5 . For this needle length range, the end of the needle at one limit, $L/D=1.5$, is located farther from the butt-end than the detached bow shock wave which occurred in the case of flow without a needle at the body front. For the other limit, $L/D=0.5$, the needle is located completely inside the compression shock layer, i.e. closer to the butt-end than the corresponding detached bow shock wave. As a result of this analysis, the following needle geometric parameters were chosen: $D/L = 0.05; 0.81; 0.1$, i.e. for the given model size, the needle diameters are: $d=4; 6.5$; and 8mm .

Optical methods of flow visualization were employed for better understanding of this phenomenon and for explanation of the force aerodynamic characteristic changes. They include a traditional shlieren method and high resolution video filming of the unsteady pulsation regimes. In Figure 3, the main models tested in supersonic flow with Mach number, $M=3$, at zero angle of attack are shown. From the left to the right, the first row: 1)-butt-end without needles; 2)-4) –for 5 thin needles model of thickness, $d/D=0.05$, and different needle lengths, $L/D=0.5, 1.0$ and 1.5 . In the second row: 5)-7)- b), c) -with single needle for two different instants of pulsation flow regime.

Several additional experimental tests were conducted with the purpose to determine the influence of multi-needle ($n>5$) and shell application to the force coefficients. The needle numbers were: $n=53$ and $n=103$. These needles are mounted symmetrically along the coincident circles located from the circle center on the radial distances: $R=0; 5; \dots 35\text{mm}$. Recall that the butt-end circle diameter is $D=80\text{mm}$. A drag coefficient comparison for all considered cases, $n=1; 5; 53$ and 103 illustrates a preferable application for drag reduction of single needles.

Thus, the principal conclusions of these test results for spikes are: multiple spike/needle application leads to decrease of drag reduction benefits by comparison with the case of one central mounted needle at the front of a blunt body, as well as in longitudinal moment, but increase lift benefits.

7.2.2 Experimental test results: Air, Liquid and Solid Particles Jet Injection. The basic idea of this research was to apply liquid or particle injection to control shock waves and provide cooling for body in high-speed flows. Two experimental test sets have been completed for this purpose: attaining injection of a liquid jet and of solid particles against a supersonic flow from a blunt body. In the first case, the nonfreezing viscous liquid (antifreeze) jet was injected from the central part of the blunt body through a nozzle of diameter, $D_n/D=0.05$. The total pressure reached up to $\sim 100\text{ atm}$. The experimental test program included fixed free stream Mach number, $M = 3.0$, and five different total pressure values. The drag coefficient of the cylindrical butt-end model was measured, and photos of the flows around this model were analyzed. Shlieren photos of two, steady and unsteady interaction regimes for water jet injection were obtained. These regimes are illustrated in Figures 3a,b. Dependence of a body drag coefficient, C_D , against P_0 It was observed that liquid jet injection leads to the jet breaking up at a very small distance from the butt-end, and, also, leads to reduction of the detached shock wave inclination on the periphery or even to its complete elimination. With increase of the total pressure in the nozzle antechamber, the drag coefficient of the butt-end model, C_D , is reduced up to $\sim 30\%$. This reduction is a bit less for the case of the nozzle with the diameter, $D_n/D=0.025$ than for the case of the nozzle diameter, $D_n/D=0.05$. For solid particle injection, a bigger nozzle diameter was manufactured, $D_n/D=0.1$. Three types of various density particles were tested: millet, semolina and quartz sand. The

sizes (diameters) were $d_p=0.2$ mm or $d_p=0.4$ mm. The same total pressure in the nozzle antechamber could be reached, ~ 100 atm. Appropriate schlieren photos of the flows have shown that injected particles smash and destroy the bow shock waves detached at the butt-end model. It is observed that particle injection instead of a liquid jet leads to butt-end drag reduction up to ~ 10 % for smaller total pressure values in the nozzle antechamber (~ 20 atm.). Then the drag coefficient increases. In Figures 4, dependence of a butt-end drag coefficient, C_D , vs total pressure values in the nozzle antechamber is illustrated for different particles, liquid and air injection. One can see that use of liquid antifreeze is preferable by comparison with others. We are planning to develop this research: to carry out experimental tests of supersonic and subsonic flows around the hemispherical blunt body with single and multiple needles, and, also, to repeat previous experimental tests injecting thin nonfreezing jets of small viscosity.

7.2.3 Numerical Simulation Test Results: Spike-Nosed Blunt Bodies. Numerical simulation tests for the 1-needle model were conducted using the IM/MSU Russian code during the visit of two Russian scientists, Drs. Valery G. Gromov and Vladimir I. Sakharov, to the HU/FM&AL over January-March, 2001. This code is based on the Navier-Stokes equations for modeling of gas-dynamic and chemical processes which take place in the internal as well as external gas flows, such as the Half-Duct Combustor System and supersonic flow around a butt-end with needles mounted against the flow. At the present time, a supersonic flow of only one design, butt-end with 1 needle, has been analyzed numerically using this Russian code. Several results are illustrated in the AIAA paper [8]. These results were obtained using a laminar viscous gas model. Note that an oscillatory regime can be observed in this simulation. However, an application of the $k-\omega$ turbulence model has led to stabilization of this process for the same outer boundary conditions in agreement with experimental tests results known from several published papers. Numerical simulation results of 3D flows around the 1-needle model at the attack angle are also in good agreement with current experimental test results. The flow field structure as well as the aerodynamic characteristics values display differences of less than ~ 3 -5% which are within the range of measurement errors from current experimental results for these values.

Numerical simulation tests of a 2D supersonic flow for the 3-step configuration have been conducted for different free stream Mach number, $M=1.5$ -4.0 and different lengths of forward directed small height steps. This 2D problem is analogous to the problem of supersonic flow around a 2-needle model described above in the previous section. Accurate solution of this problem allows resolution of many obstacles connected with the more complicated 3D-problem solution for the flow in the 2-needles model. Some numerical simulation results obtained with the NASA CFL3D code with the $k-\omega$ turbulence model for a viscous perfect gas and with slip and no-slip boundary conditions on the solid surface of the step configuration. These results were presented at the conference and published in [6]. The main conclusion from these simulations is the same as from the experimental tests results. Namely, adding a second step does not provide any benefits for shock mitigation and respectively to drag reduction by the main step.

Currently, analogous numerical simulations are being conducted for the 3D problem at the HU/FM&AL. The example of such results is illustrated in Figure 4. Some information for supersonic flow numerical simulation with free stream Mach number, M_∞ , around 5-needles nosed butt-end at zero attack angle is presented. The NASA CFL3D code was employed, and Navier-Stokes Equation (NSE) based simulation was conducted with slip boundary conditions. Here are: a) Mach contours in the symmetry XZ-plane; b) Mach contours in the cross section $X=\text{const}$ at the butt-end front wall; c)

portion of employed grid in this cross section; d) 3D grid for the domain between two symmetry planes. This grid contents 15 blocks.

7.2.4 Experimental test results: Solid particles and Jet Injection An existing discrete-trajectory approach using the two-phase version of the 1st order Godunov scheme for numerical simulation of unsteady and steady 2D and axisymmetric inviscid flows [4] was improved. The improvement lays in two directions: 1) use of “almost adaptive” grids for gas phase and 2) application of a 2nd order numerical scheme for gas phase and calculation of particle trajectories and their parameters along these trajectories. By such improvements, more exact numerical results were obtained for the problem of supersonic flow at the blunt body with solid particle injection against a flow. Several numerical simulations were conducted for the cases tested experimentally in the IM/MSU aerodynamic wind tunnel A-7. In particular, for the quartz sand particles with the sizes $d_p=0.2$ mm and $d_p=0.4$ mm, comparison of maximal particle penetration upstream to the supersonic flow with free stream Mach number, $M_\infty=3$, shows very good agreement between numerical and experimental results. In Figure 5 numerical simulation results are shown for millet particles with average diameter, $d=1.5$ mm. The gas flow structures obtained numerically (Mach contours) and experimentally (schlieren photo) are also very similar. At the present time, we are developing the discrete-trajectory method for the NASA CFL3d code for numerical simulation of two-phase flows based on the NSE approximation for gas phase.

7.3 Hampton University Student Research, Training and Studying Activity. These activities are illustrated in Figures 6-8. Note that 5 students shown above in paragraph 6) were co-authors of two annual reports. These reports were presented at the Historically Black Colleges and Universities/Other Minority Universities (HBCUs/OMUs) Research Conference on April 17-18, 2001, at the Ohio Aerospace Institute/NASA Glenn Research Center, Cleveland, OH, and abstracts have been published in this conference proceeding. In addition, a new course for HU students entitled “Advanced Aerodynamics and Aircraft Performance” lectured in the spring semester by the FM&AL researchers Dr. M. Gilinsky and N. Sckholnikov and Full semester by Dr. M. Gilinsky and L.G. Mosiane with training in experimental tests using LSW I.

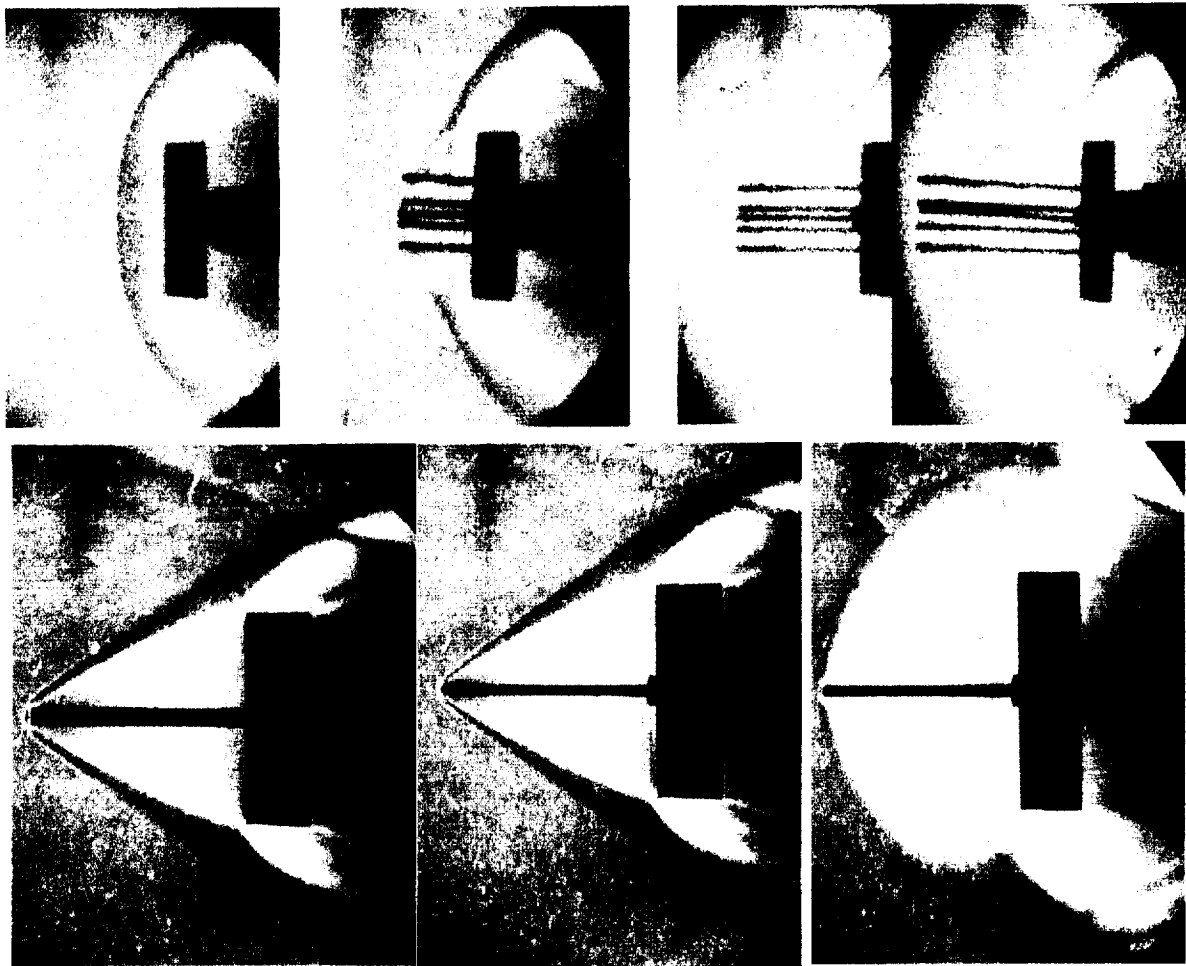


Fig. 3 Experimental Test Results for Spike-Nosed Blunt Bodies. Optical visualization obtained by the shlieren method. The main models were tested in supersonic flow with Mach number, $M=3$, at zero angle of attack. These results are shown from the left to the right: the first row: 1)-butt-end without needles; 2)-4) -for 5 thin needles model of thickness, $d/D=0.1$ and 0.05 , and different needle lengths, $L/D=0.5$; 1.0 and 1.5 . The second row: 5)-7) -with single needle of length, $L/D=1.5$, 5) corresponds to d/D to $d/D=0.05$; the last two pictures are for two different instants of pulsation flow regime.

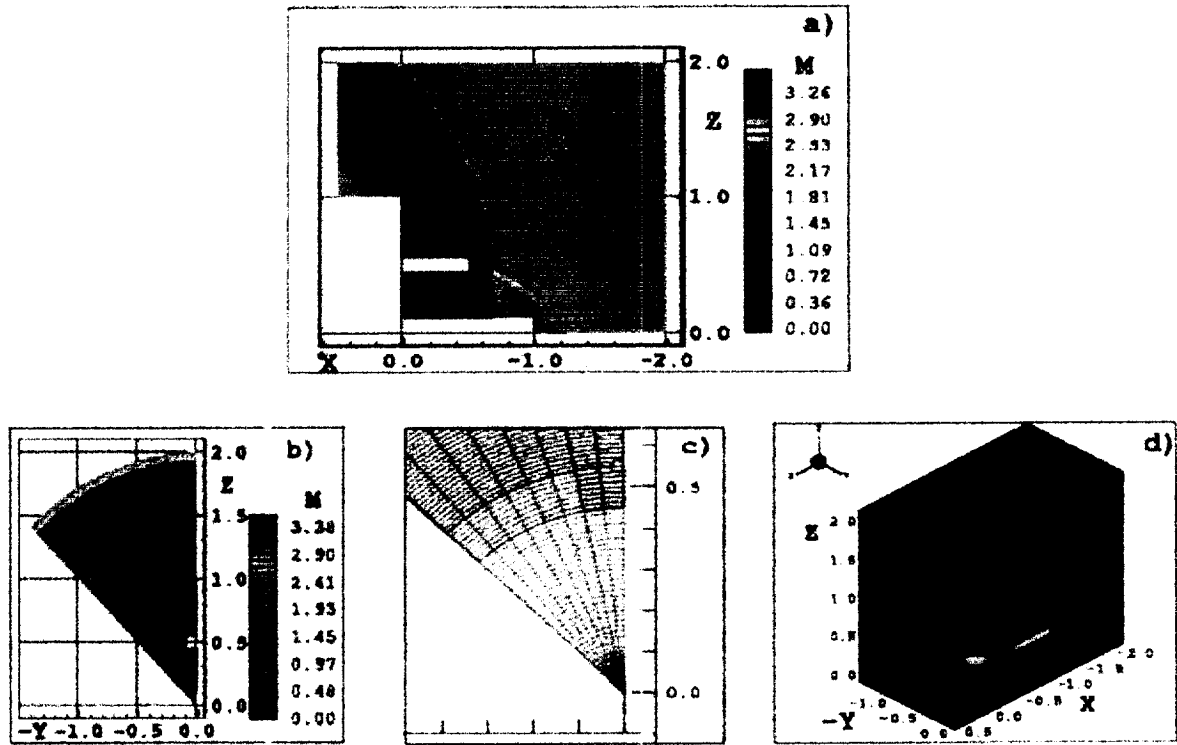


Fig.4 Mach 3 Supersonic Flow Numerical Simulation Results around 5-Needle Nosed Butt-End at Zero Attack Angle. NASA CFL3D code. Navier-Stokes based simulation with slip boundary conditions. a) Mach contours in the symmetry XZ-plane; b) Mach contours in the cross section $X=\text{const}$ at the butt-end front wall; c) portion of grid employed in this cross section; d) 3D grid for the domain between two symmetry planes. This grid contains 15 blocks.

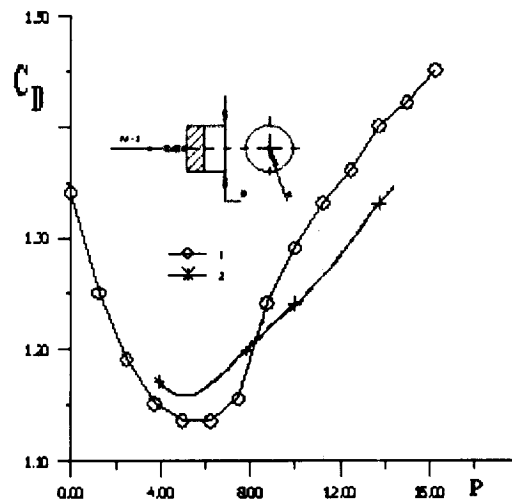


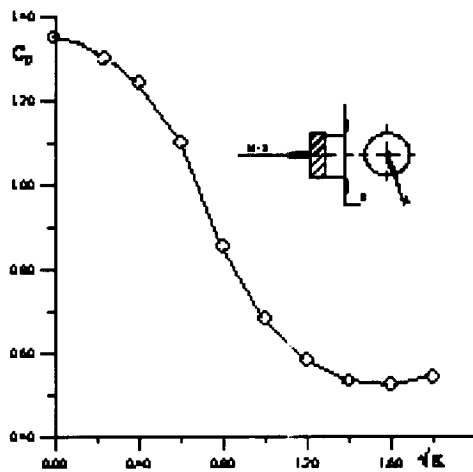
Fig. 5 Comparison of experimental and numerical simulation test results for solid particles injection. Free stream Mach number, $M_\infty=3.0$; 1-experiments for millet particles, $d=1.5\text{mm}$; 2- numerical simulation results.



a)



b)



c)

Fig.5 Experimental test results of water jet injection through butt-end against the supersonic flow obtained in the IM/MSU aerodynamic wind tunnel A-7.

a) Shlieren photo of stationary regime supersonic flow with Mach number, $M=3.0$, around butt-end with injected liquid jet.

b) Shlieren photo of unsteady regime supersonic flow with Mach number, $M=3.0$, around butt-end with injected liquid jet.

c) Drag coefficient C_D vs non-dimensional impulse coefficient, $K = \rho_j V_j^2 / \rho_\infty V_\infty^2$, where index "j" is for injected liquid jet, index " ∞ " is for free stream flow; $M = 3.0$, $d/D = 0.05$. The liquid is mixture: ethylene glycol (30-50%) and water (70-50%).



Fig.6 View of the Hampton University Low Speed Wind Tunnel (LSWT). This tunnel is housed in the Experimental Hall at the Fluid Mechanics and Acoustics Laboratory (FM&AL). Principal Investigator, Dr. Mikhail Gilinsky and Undergraduate Research Assistants, Casey Alexander, discuss the next experimental setup.

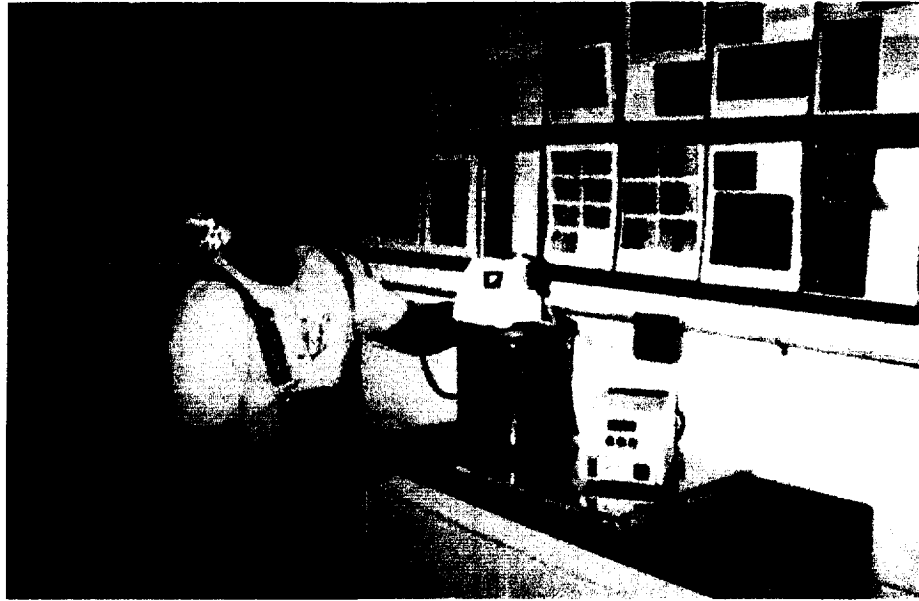


Fig.7 Hampton University Low Speed Wind Tunnel (LSWT) at the Fluid Mechanics and Acoustics Laboratory (FM&AL). Experimental hall. Undergraduate Research Assistant, Norman Njoroge (Aviation Department) conducts experimental test with Möbius-shaped screws.

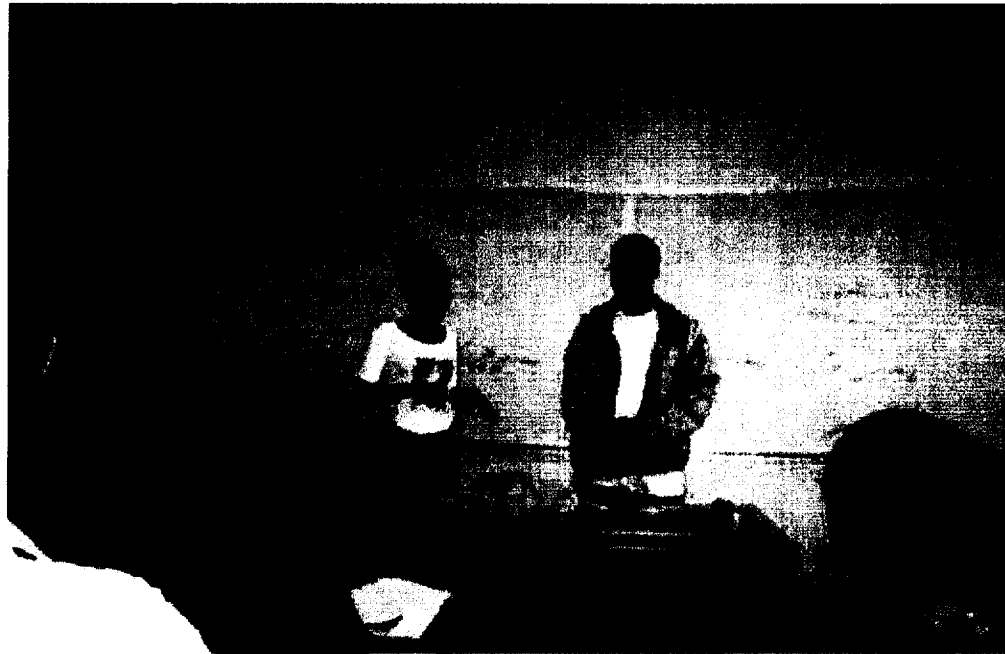


Fig.8 Hampton University students attend the new course: “Advanced Aerodynamics and Aircraft Performance” lectured in the spring semester by the FM&AL researchers, Dr. M. Gilinsky and N. Sckholnikov with training in experimental tests using LSWT. The picture depicts presentation of the joint project by two students before final exams.

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